GRASSROOTS JOURNALS

Grassroots Journal of Natural Resources, Vol.7 No.2 (August 2024)
ISSN: 2581-6853 | CODEN: GJNRA9 | Published by The Grassroots Institute
Website: https://grassrootsjournals.org/gjnr | Main Indexing: Scopus and WoS

ISSN 2581-6853 | 7(2) Aug 2024

M – 00405 | Research Article

Analysis of the Impact of Climate Change on the Vegetation of the Perehinsk Territorial Community in Ukraine

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How to cite this paper: Ivanyshyn, V. and Kasiyanchuk, D. (2024). Analysis of the Impact of Climate Change on the Vegetation of the Perehinsk Territorial Community in Ukraine. *Grassroots Journal of Natural Resources*, 7(2): 199-215. Doi: https://doi.org/10.33002/nr2581.6853.070210

Received: 29 May 2024
Reviewed: 10 July 2024
Provisionally Accepted: 10 July 2024
Revised: 15 July 2024
Finally Accepted: 16 July 2024
Published: 01 August 2024
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Abstract

The Carpathian region, to which the research area belongs, is one of the most forested areas of Ukraine, and at the same time the most anthropogenically loaded. Studying the vegetation cover of the territories is currently one of the most important parameters that allows us to assess the state of the environment. The paper analyzes the change in the state of vegetation based on the NDVI index using Google Earth Engine (GEE) for the period between 2018 and 2023, with the construction of a difference index. The satellite image interpretation data allowed us to summarise the dynamics of the vegetation index change for two similar periods, in particular, for 2018 it is 0.464, for 2023 it is 0.330. The average difference value for the study area is 0.229. Taking into account dynamic climate change and its parameters such as precipitation, air temperature, surface temperature, wind speed, NDVI and NDWI indices, a correlation analysis was performed to identify the relationship between changes in vegetation cover and weather conditions. Statistical analysis of the data allowed us to identify the main groups of factors that have the greatest impact on the NDVI index, namely temperature and precipitation. However, the NDWI moisture index is in a clear inverse correlation, which confirms the significant impact of global temperatures on the unevenness of precipitation, especially during the 2018 floods. It is worth noting that the movement of air masses, which was determined through the average annual wind speed, gives an understanding of how changes in temperature above the ground affect the moisture content of vegetation.
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Keywords

Vegetation; Forest; Remote sensing; Climate; NDVI

Introduction

The study of forests in the context of intensive industrial development and global climate change is an important part of ecosystem

assessment. The Carpathian Mountains of Ukraine are one of the most important forest regions in the country. Forest plantations account for 52.8% of the total forest area. The height limit of the plantations ranges from 150 m to 1600 m. The main forest species are beech, spruce, hornbeam and oak. Common admixtures are sycamore, ash, etc.

Hensiruk (1964) was the first to make a comprehensive analysis of the forests of the Ukrainian Carpathians. The study of Yuzyk (2022) collects the results of researches on the forests of the Ukrainian Carpathians by many scientists from the territory of modern Ukraine, foreign researchers, as well as environmentalists from the states and empires, which, in the past, included the mentioned mountain ranges. Along with intensive development, forests are becoming a factor closely linked to the development of exogenous geological processes such as landslides. Hablovskyi *et al*. (2023) and Kasiyanchuk and Shtohryn (2021) analyse the effect of distance to the forest as a factor in causing landslides in the spatial and temporal spectrum.

Climate change is one of the most unpredictable areas of environmental change in terms of short-term prospects. The Vegetation Index is one of the indicators in temperate latitudes for analysing global temperature fluctuations on meteorological indicators and their impact on vegetation. The search for statistical dependencies, probability estimation and forecasting are the main tasks that scientists are currently working on the most (Marusig *et al*., 2020; Patil *et al*., 2024). The Carpathian region is an important supplier of not only timber, but also ensures the functioning of the tourism sector as an area with conditionally clean air and mountainous landscapes. However, changes in industrial logging, ill-conceived economic activities and other environmental problems in the region such as floods are causing negative changes in the overall condition of the forest cover of the territory.

Mountainous conditions, complex landscapes and anthropogenic pressures are becoming increasingly important for the management and analysis of the condition of vegetation, especially forests. The need to find ways to analyse not only changes in their quantitative and qualitative state is particularly relevant in the context of individual territorial units. This allows for a unified strategy for sustainable community development based on an integrated approach using geographic information systems (GIS). Regions with significant forest reserves are particularly in need of clear planning to balance economic stability and environmental security.

Overview of the Area and Study Trends

One of the main tasks of ensuring a high-quality information approach to the development of Amalgamated Territorial Community (ATCs) based on the content of the administrative reform is the development of regional GIS, which is the main objective of this study. The territory of the Perehinsk community (Figure 1) lies within the Limnytsia river basin, which is one of the cleanest rivers not only in Ukraine but also in Europe. It is well known that the formation of the river's water balance often depends on the condition and quality of the vegetation cover. An equally important factor in shaping the structure of the territory's forest plantations is its altitude gradation from the Carpathian Mountains to the Precarpathian trough, which characterises the region as a zone of coniferous forests in the highlands and mixed forests in the Limnytsia river

valley. The region's main industry is timber processing, so the study of the vegetation index is important not only for modelling and analysing economic benefits and risks, but also for studying the impact of global climate change and unauthorised logging on the ecosystem as a whole.

Figure 2 presents an analysis of the state of the forest cover by materials of Global Forest Watch (GFW). It is an online platform that provides data and tools for monitoring forests. By harnessing cutting-edge technology, GFW allows anyone to access near real-time information about where and how forests are changing around the world. Analyzing the data, it should be noted that forest reserves have decreased by 18% over the past 23 years.

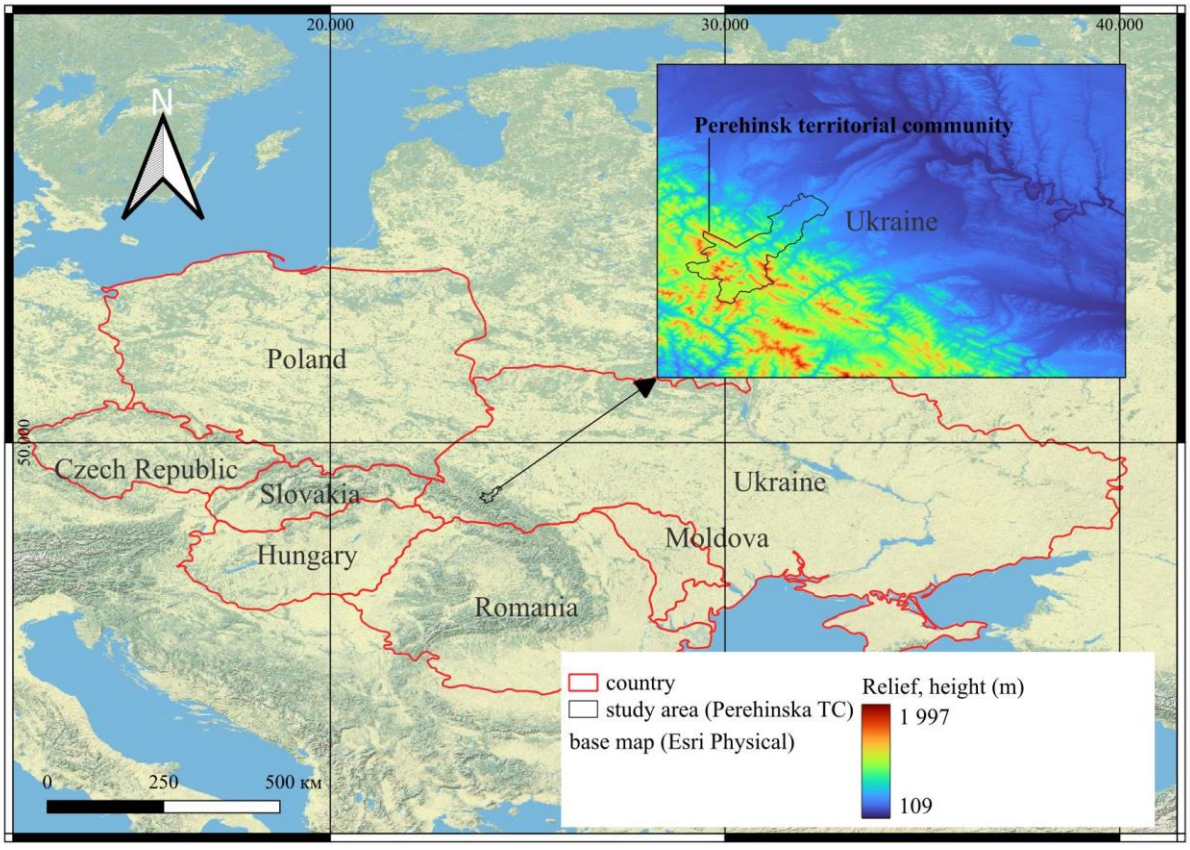


Figure 1: The map of the territory under study

The study of forest plantations is a multidisciplinary process that includes forest condition assessment methods, especially using modern GIS based on remote sensing data. Chughtai, Abbasi and Karas (2021) evaluated the most commonly used method for land cover change detection using the Maximum Likelihood Classifier (MLC), which gave the best results. Jujea *et al.* (2023) used supervised mapping on satellite imagery using the European Space Agency (ESA) SNAP programme from LANDSAT databases to assess landscape change in the Romanian Carpathians over the period 1990-2021. Reshetnyk and Kotsyubynskyi (2024) analysed that the use of drones in combination with GIS allows the creation of detailed mapping materials and analysis based on geospatial data. This approach helps optimise the use of forest resources and

management processes, increase the efficiency of land use and reduce the impact of economic activities on forest ecosystems.

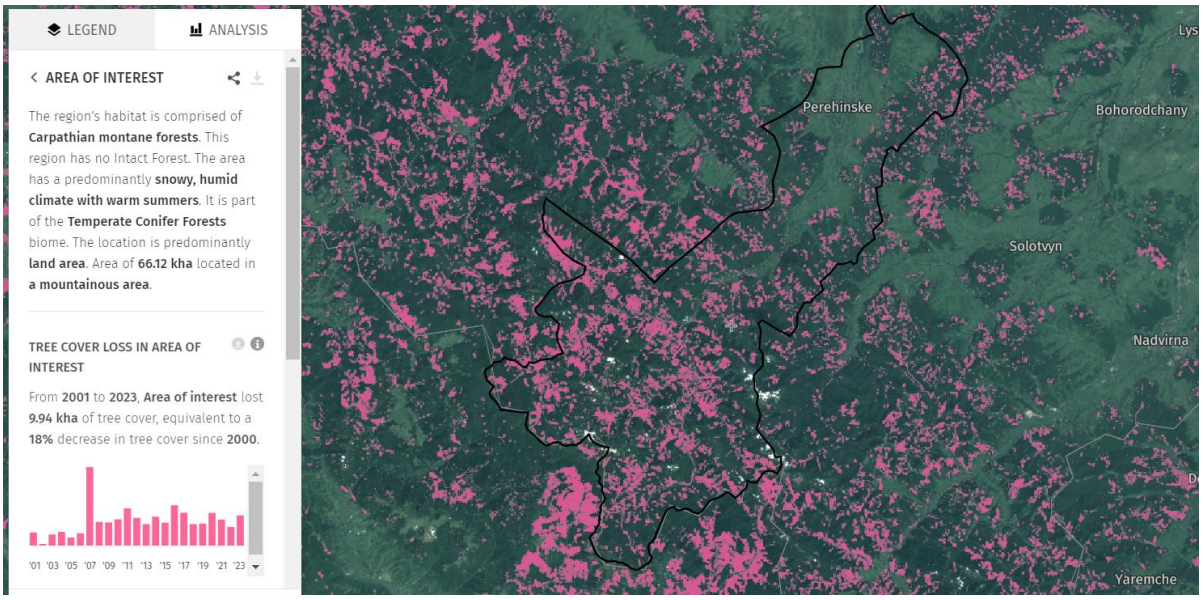

LEGEND
ANALYSIS
AREA OF INTEREST
The region's habitat is comprised of Carpathian montane forests. This region has no Intact Forest. The area has a predominantly snowy, humid climate with warm summers. It is part of the Temperate Conifer Forests biome. The location is predominantly land area. Area of 66.12 kha located in a mountainous area.
TREE COVER LOSS IN AREA OF INTEREST
From 2001 to 2023, Area of interest lost 9.94 kha of tree cover, equivalent to a 18% decrease in tree cover since 2000.
'01 '03 '05 '07 '09 '11 '13 '15 '17 '19 '21 '23
Perehinske
Bohorodchany
Solotvyn
Nadvirna
Yaremche

Figure 2: State of forests by GFW materials
(Source: map – https://gfw.global/3K8Vsnke; analysis–- https://gfw.global/4aoCmo4)

Burshtynska *et al*. (2019) applied a methodology based on the use of satellite imagery with different spectral characteristics and resolution, as well as imagery obtained from UAVs, to monitor the forests of the Tukhlyansk forestry. Using the Normalised Difference Vegetation Index (NDVI) to detect different land cover changes, Alonso, Picos and Armesto (2023) and Moon and Solomon (2023) developed a methodology to produce an integrated land cover map.

Methodology

Remote sensing, the process of collecting data from a distance, has revolutionized our ability to monitor and understand the Earth's surface. Among the plethora of indices and metrics used in remote sensing, the Normalized Difference Vegetation Index (NDVI) stands out as a powerful tool for assessing vegetation health and dynamics. Developed in the 1970s by Rouse *et al.* (1973), NDVI has ever since become a cornerstone in environmental monitoring, agricultural management, and land cover analysis. At its core, NDVI quantifies the density and health of vegetation by leveraging the reflectance properties of two key wavelengths: near-infrared (NIR) and red light. The formula for NDVI is straightforward (1):

$$NDVI= (NIR+Red)/(NIR−Red), \quad (1)$$

where NIR is the reflectance in the near-infrared spectrum and Red is the reflectance in the red spectrum. The resulting values range from -1 to 1, with higher values indicating denser and healthier vegetation. Negative values typically represent water bodies or clouds, while values close to zero suggest barren land or urban areas with little to no vegetation.

The strength of NDVI lies in its sensitivity to chlorophyll content and canopy structure. Healthy vegetation absorbs most of the visible red light for photosynthesis, while reflecting a significant portion of NIR light. Consequently, the NDVI values for healthy vegetation are relatively high due to the large NIR reflectance and low red reflectance. Conversely, stressed or sparse vegetation exhibits lower NDVI values, as seen in areas affected by drought, disease, or human activity. One of the key advantages of NDVI is its applicability across various spatial and temporal scales. It can be computed from multispectral satellite imagery, aerial photography, or ground-based sensors, offering insights into vegetation dynamics at local, regional, and global levels. Additionally, NDVI facilitates the monitoring of seasonal changes, phenological shifts, and long-term trends in vegetation cover, providing invaluable information for land management, biodiversity conservation, and climate change research.

In agricultural contexts, NDVI is widely used to optimize crop production, monitor crop health, and assess the effectiveness of irrigation and fertilizer applications. By mapping NDVI spatial patterns within fields, farmers can identify areas of concern, implement targeted interventions, and maximize yields while minimizing inputs. Similarly, conservationists leverage NDVI to evaluate habitat quality, track deforestation, and prioritize areas for restoration efforts.

The figure 3 shows the general structure that was used as a basis for this study of the territory.

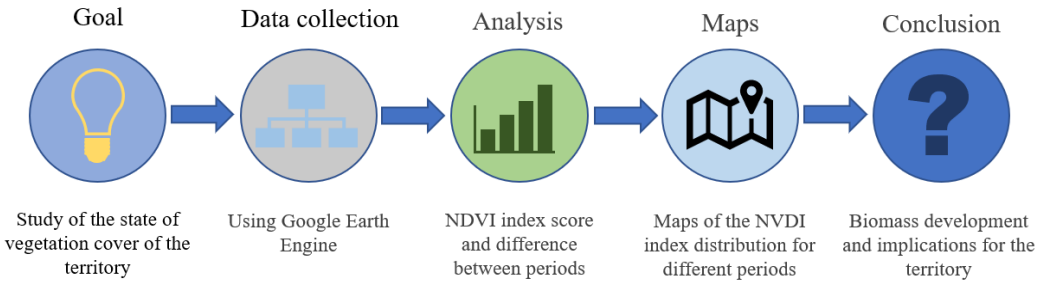

Goal
Data collection
Analysis
Maps
Conclusion
Study of the state of vegetation cover of the territory
Using Google Earth Engine
NDVI index score and difference between periods
Maps of the NVDI index distribution for different periods
Biomass development and implications for the territory

Figure 3: Structure of the study

To achieve the goals of the work (Figure 3), it was necessary to:

- to study the main methodological indicators that affect the development of vegetation: wind speed, precipitation, temperature;
- using the Java Script code in the Google Earth Engine environment, select data for the selected periods: meteorological indicators, NDVI, NDWI;
- calculate the average values of the NDVI index during the active growing season for 2018 and 2023;
- using the methods of geo-analytical and geostatistical analyses in the QGIS software, perform image classification;
- systematise all factors by month;
- analyse the relationship between NDVI and NDWI from 2018 to 2023; and
- assess the interdependence of the factors based on correlation and cluster analyses.

Analysis of the NDVI

Downloading a large number of satellite images and organising them for research takes time and a large amount of storage space. When using Google Earth Engine (GEE), there is no need to download satellite imagery, which is an advantage. The Sentinel-2 satellite images with cloud cover not exceeding 10% were used in the script (Figure 4). The basis for the analysis of climate parameters is the following data Muñoz Sabater (2019).

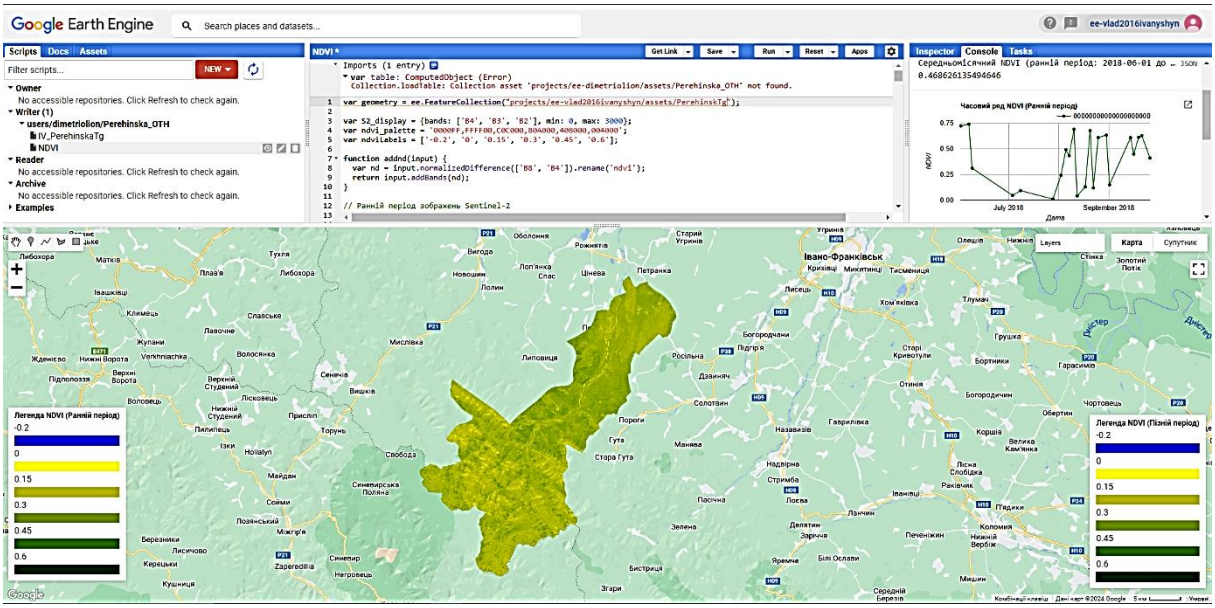


Figure 4: Calculating of the NDVI index for community (by GEE) (Ivanyshyn and Kasiyanchuk, 2024)

The data show a significant difference in biomass production between 2018 and 2023 (Table 1, Figure 5). The NDVI index in 2018 is higher due to more favourable conditions for vegetation development. Humidity at that time was quite high, precipitation was frequent and floods were not uncommon. The situation in 2023, as can be seen from the data obtained, was radically different; it was a dry period accompanied by extreme heat, precipitation was not as frequent as in 2018. The ability of tree leaves to photosynthesise decreases when their temperature becomes too high. Due to the abnormal heat, some of the leaves may have crossed a critical temperature threshold after which their ability to photosynthesise is impaired.

Table 1: Average values of t*he NDVI index*

Month	*Years*	
	2018	*2023*
June	0.591	0.337
July	0.051	0.387
August	0.407	0.284
September	0.477	0.314
Average	*0.464*	*0.330*

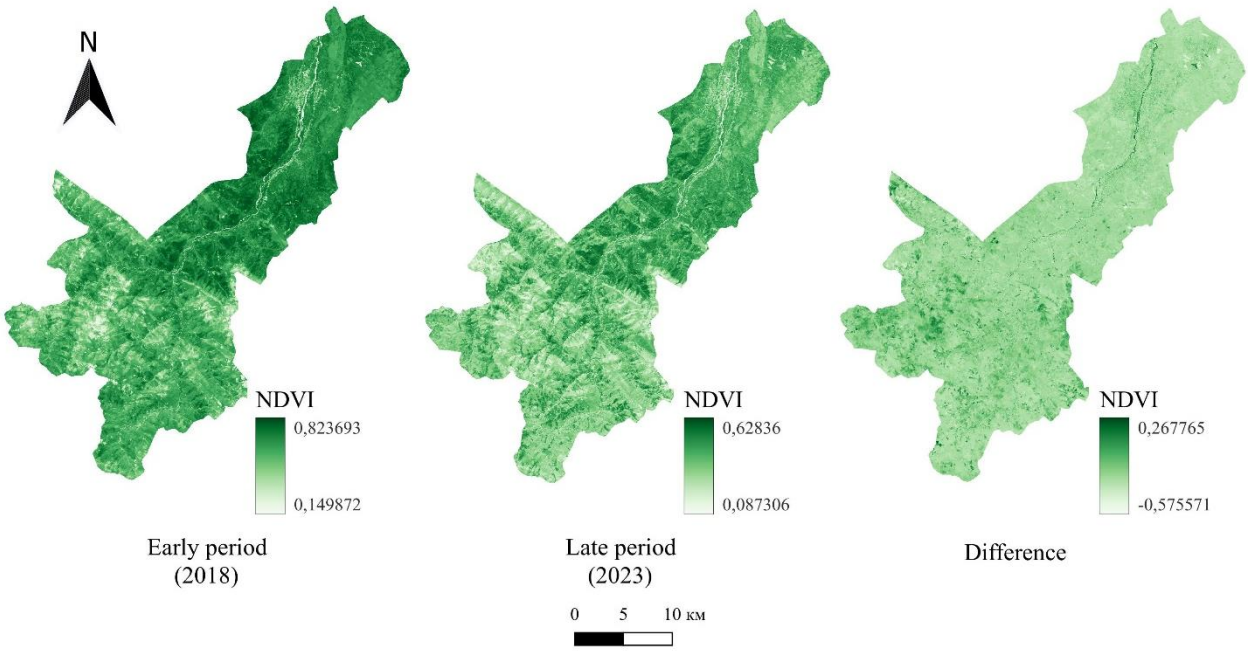


Figure 5: NDVI index of Perehinsk territorial community

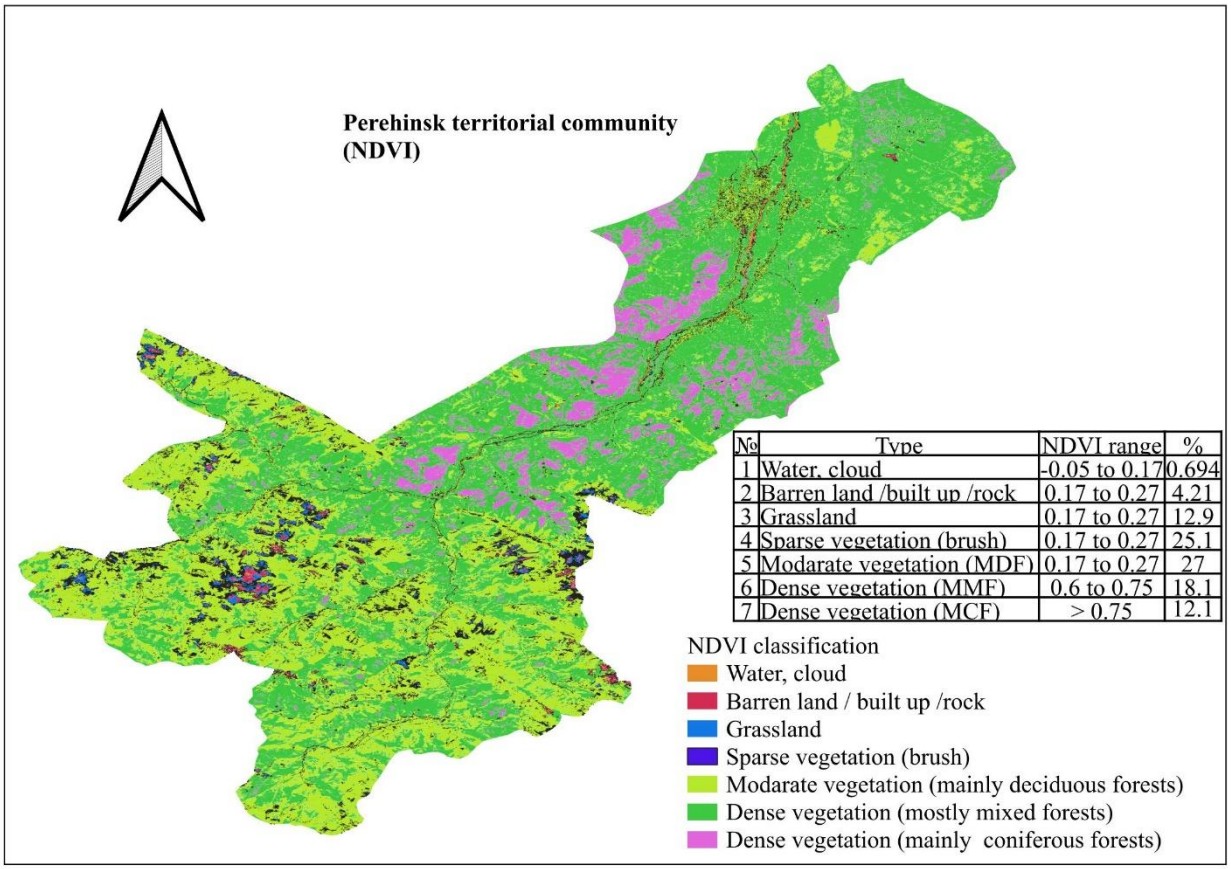

Perehinsk territorial community
(NDVI)
№ Type NDVI range %
1 Water, cloud -0.05 to 0.17 0.694
2 Barren land /built up /rock 0.17 to 0.27 4.21
3 Grassland 0.17 to 0.27 12.9
4 Sparse vegetation (brush) 0.17 to 0.27 25.1
5 Modarate vegetation (MDF) 0.17 to 0.27 27
6 Dense vegetation (MMF) 0.6 to 0.75 18.1
7 Dense vegetation (MCF) > 0.75 12.1
NDVI classification
Water, cloud
Barren land / built up /rock
Grassland
Sparse vegetation (brush)
Modarate vegetation (mainly deciduous forests)
Dense vegetation (mostly mixed forests)
Dense vegetation (mainly coniferous forests)

Figure 6: NDVI cclassification

Analysing the results (Figure 5), it is difficult to assess which areas were most affected by this or that factor. Therefore, an additional difference model was built. The average difference value for the study area is -0.229. This is a fairly large figure. And as can be seen from the model, it is the mountainous areas that have undergone the greatest changes, which directly indicates significant deforestation in the study area.

An important stage of the study is the classification of NDVI in order to estimate the area of a particular type according to the index value. Figure 6 shows the classification map, which outlines the 7 types that best characterise the heterogeneity of the landscape of the study area.

Analysis of the Main Meteorological Parameters

Climate change is an important indicator for assessing the state of the environment. Figure 7 shows the dynamics of temperature and precipitation changes over the period 2001-2022. It can be seen quite clearly that the average annual temperature is rising, and the negative changes are irreversible for the ecosystem. The rise in temperature also leads to an increase in intense precipitation, which is increasingly evident in floods and flood periods that are characteristic of the entire region. Such changes are crucial for further analysis and understanding, as the former affect the ability to actively grow and the latter affect the moisture content, which is often excessive only in certain periods.

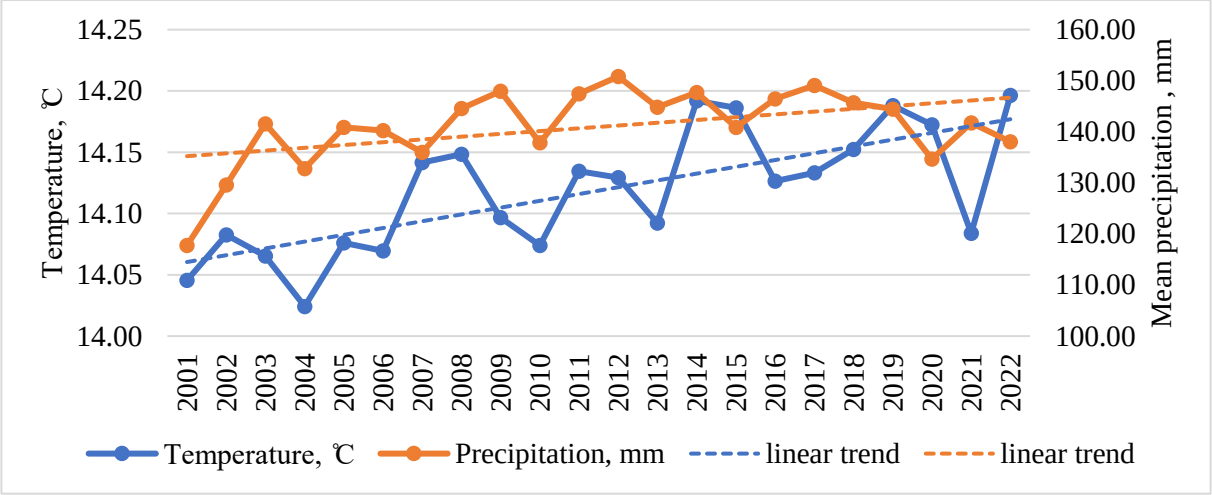


Figure 7: Dynamics of temperature and precipitation in 2001-2022

The impact of climate on NDVI is one of the aspects of vegetation assessment. Global warming, changes in precipitation patterns and an increase in the frequency of extreme weather events can cause changes in vegetation cover, which is reflected in NDVI. Studying such changes can help us better understand how climate factors affect ecosystems and predict future changes.

To study the likelihood of climate indicators affecting the state of vegetation, we analysed the data selected when writing the code. In particular, these are the values of the NDVI index itself, the NDWI water index, air temperature at a height of 2 m, precipitation, and wind speed. To study the temporal characteristics of the state of

vegetation cover, the water saturation index (NDWI) is most often used in conjunction with the NDVI index itself. Such a comparative characteristic at the initial stage will allow to assess the possible relationships between the state of vegetation and soil moisture saturation. To analyse the satellite images, we used Sentinel-2 satellite data and formed a time series for the period from 2018 to 2023 by month (Figure 8).

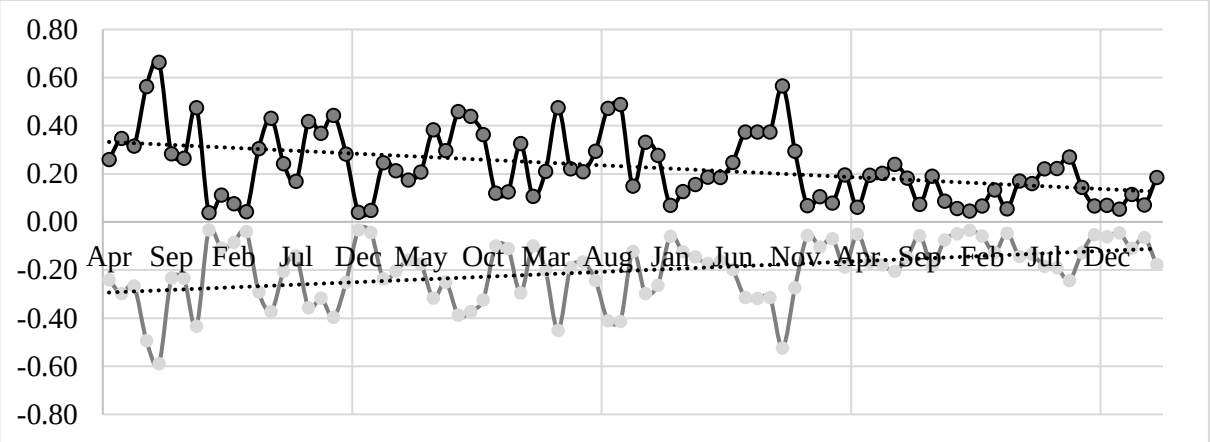


Figure 8: Charts of NDVI and NDWI from 2018 to 2023

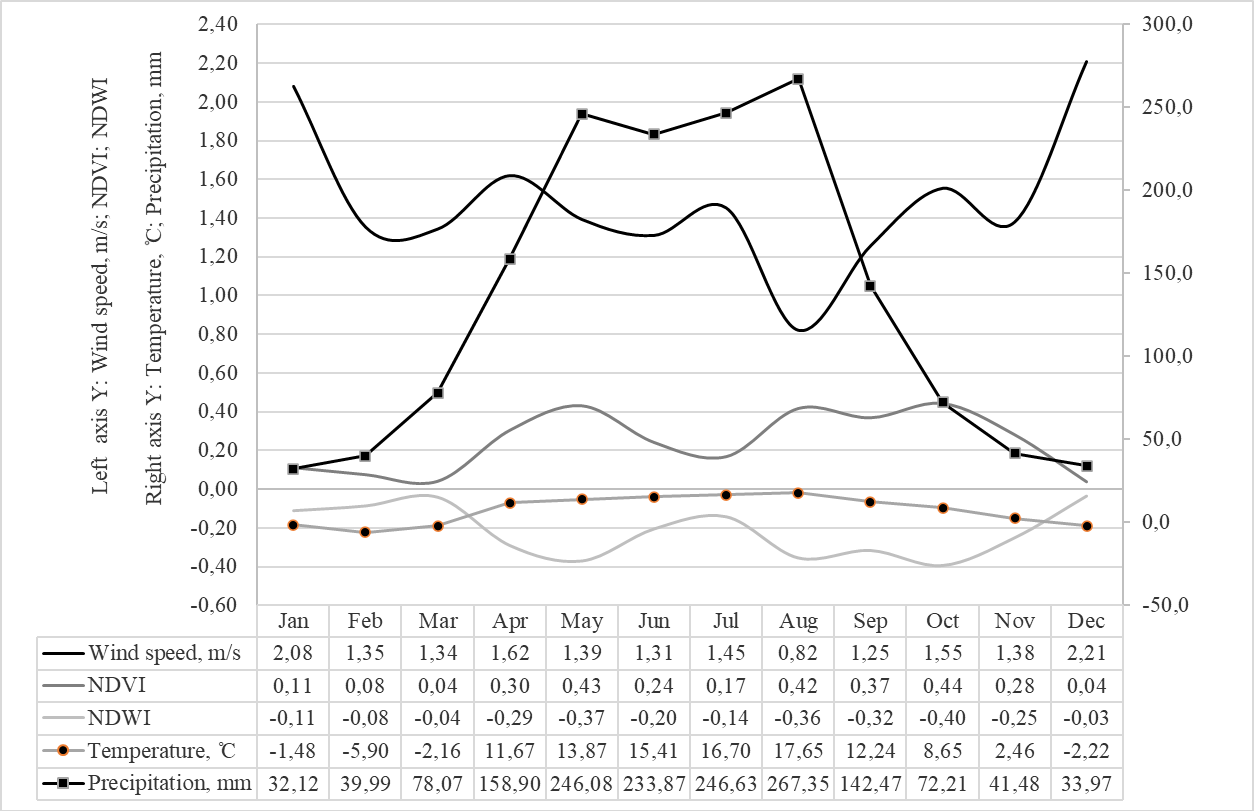
Figure 8 clearly shows the interdependence between the indices. Thus, the assumption that the basis of vegetation development in the region has a clear dependence on moisture saturation makes sense. However, there is another negative downward trend in both the vegetation index and the water saturation index. Unfortunately, this negative trend is observed for all river basins in the Carpathian region, as outlined in Gavrilyuk and Kasiyanchuk (2024), open-water wetlandscape restoration by Ioana-Toroimac *et al.* (2024) or an example of cities in the work of Yedla and Reddya (2024).

Estimation of climate parameters is a complex process and requires significant time series, which is not always available for all selected meteorological indicators (Figure 8). Therefore, for the analysis, we selected climate indicators that can characterise the dynamics for 2018. (Table 2) for the annual (Table 2 a) and most productive growing season (Table 2 b). Statistical analysis is the basic one in assessing the interdependencies between the main parameters. Table 2 shows the correlation matrix, which shows how this or that factor is interconnected with another.

The main feature of meteorological and climatic indicators is their seasonality (Figure 9), which we can clearly see within the territory of the Perehynsk territorial community. This component determines not only the basis of the indices, but also their numerical values. The increase in temperature and precipitation corresponds to the state of the vegetation cover due to intensive growth during the growing season.

A correlation matrix is one of the best ways to analyse the dependence of factors on each other. This allows us to conduct not only a spatial but also a temporal analysis of changes in the NDVI index in the future, which becomes a logical basis for further research. First of all, it should be noted that the NDVI and NDWI parameters are completely asynchronous, as we have already described above. The relationship between the

parameters of vegetation and temperature is understandable, since the NDVI index is meaningful only in the warm period when weather conditions are favourable for the development of vegetation.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind speed, m/s	2,08	1,35	1,34	1,62	1,39	1,31	1,45	0,82	1,25	1,55	1,38	2,21
NDVI	0,11	0,08	0,04	0,30	0,43	0,24	0,17	0,42	0,37	0,44	0,28	0,04
NDWI	-0,11	-0,08	-0,04	-0,29	-0,37	-0,20	-0,14	-0,36	-0,32	-0,40	-0,25	-0,03
Temperature, ℃	-1,48	-5,90	-2,16	11,67	13,87	15,41	16,70	17,65	12,24	8,65	2,46	-2,22
Precipitation, mm	32,12	39,99	78,07	158,90	246,08	233,87	246,63	267,35	142,47	72,21	41,48	33,97

Figure 9: Charts of the main parameters for 2018

It is more difficult, although with high correlation values, to talk about a clear relationship between rainfall and wind. Although the first factor is as formative in the development of vegetation as temperature. Obviously, vegetation growth is most active in the rainy season. However, it should be understood that the Perehynska community is heterogeneous in terms of landscape zoning (Adamenko, Rudko and Kovalchuk, 1990) and is naturally defined by the Limnytsia River basin, from the Horhany mountain range with its outcrops of indigenous rocks to the flat valleys of the basin with its numerous tributaries. Such landscape and geological conditions determine the distribution of forests and agricultural development opportunities. This is what we see in the correlation matrix.

For the period from June to September 2018 (Table 2b), the values have changed compared to the annual average. Wind speed: the signs have not changed, and the increase in the relationship between some parameters is due to the movements of cyclones and anticyclones (which needs to be studied for similar periods in the future); Air temperature: the increase in temperature has a negative impact on the state of vegetation, although it is directly proportional to precipitation, and now it is traced by the corresponding positive number and the NDWI index (which may characterise the increase in recent years in unevenly distributed precipitation in the monthly cycle, and

the increase in the number of excessively intense short-term precipitation events, which often have a negative impact due to the development of floods and floods); Precipitation: the greatest change, as in the previous factor, was in the relationship with the indices (which is also evidence of the negative impact of excessive moisture on plant condition, especially in flat areas where surface runoff is slower and contributes to waterlogging and plant growth disorders); NDVI and NDWI: the relationship between the indices has not changed, which characterises not only the growing season of 2018 but also between the study periods (Figure 9) and the dependencies described above (which confirms the significant impact of climate, mainly temperature increase and extreme precipitation on the state of vegetation cover as the basis of the global air mass cycle, which often, especially in recent periods, determine the dynamics of meteorological indicators).

Table 2: Correlation matrix
a) January – December 2018 (significant values highlighted)

Variable (mean value)	*Correlations (NDVI) Marked correlations are significant at p < .05000 N=12 (Casewise deletion of missing data)*				
	Wind speed, m/s	*Temperature, ℃*	*Precipitation, mm*	*NDVI*	*NDWI*
Wind speed, m/s	*1.0000*	-0.5262	*-0.5909*	-0.5102	0.4881
Temperature, ℃	-0.5262	*1.0000*	*0.9120*	*0.7270*	*-0.6958*
Precipitation, mm	*-0.5909*	*0.9120*	*1.0000*	0.5204	-0.4818
NDVI	-0.5102	*0.7270*	0.5204	*1.0000*	*-0.9968*
NDWI	0.4881	*-0.6958*	-0.4818	*-0.9968*	*1.0000*

b) June – September 2018 (significant values highlighted)

Variable (mean value)	*Correlations (NDVI) Marked correlations are significant at p < .05000 N=4 (Casewise deletion of missing data)*				
	Wind speed, m/s	*Temperature, ℃*	*Precipitation, mm*	*NDVI*	*NDWI*
Wind speed, m/s	*1.0000*	-0.3631	-0.3115	*-0.8602*	*0.8537*
Temperature, ℃	-0.3631	*1.0000*	*0.9867*	-0.1554	0.1674
Precipitation, mm	-0.3115	*0.9867*	*1.0000*	-0.2165	0.2289
NDVI	*-0.8602*	-0.1554	-0.2165	*1.0000*	*-0.9999*
NDWI	*0.8537*	0.1674	0.2289	*-0.9999*	*1.0000*

Based on the results, there is a clear understanding that the global challenges facing small communities today are important in developing resource management strategies. In the coming periods, environmental changes in landscapes will play a leading role in balancing the need to conserve biodiversity, the need for resources for human activities and climate change. The NDVI as one of the indicators of ecosystem health, including for the Limnytsia River basin, shows that anthropogenic impact on forests, especially in areas remote from human settlements, is extremely important. Unauthorised deforestation and the destruction of the underlying surface by wheeled vehicles leads to

a significant loss of valuable wood species that the region used to be rich in. Deforestation is a problem not only for the Perehinsk territorial community, but also for the Carpathian region of Ukraine and beyond (Antonescu, 2023).

Cluster analysis should be carried out to better understand how factors can be grouped. Figure 10 shows the cluster analysis between months and by main factors. The result shown in figure 10 gives a clear understanding that there is one clear group of temperature, precipitation, NDVI. The rise in temperature, which we can see in the figure 7, is a clear trend, and the increasing heterogeneity and unevenness of precipitation are the main factors that determine the state of the vegetation. This is proved both by high correlation values and confirmed by cluster analysis.

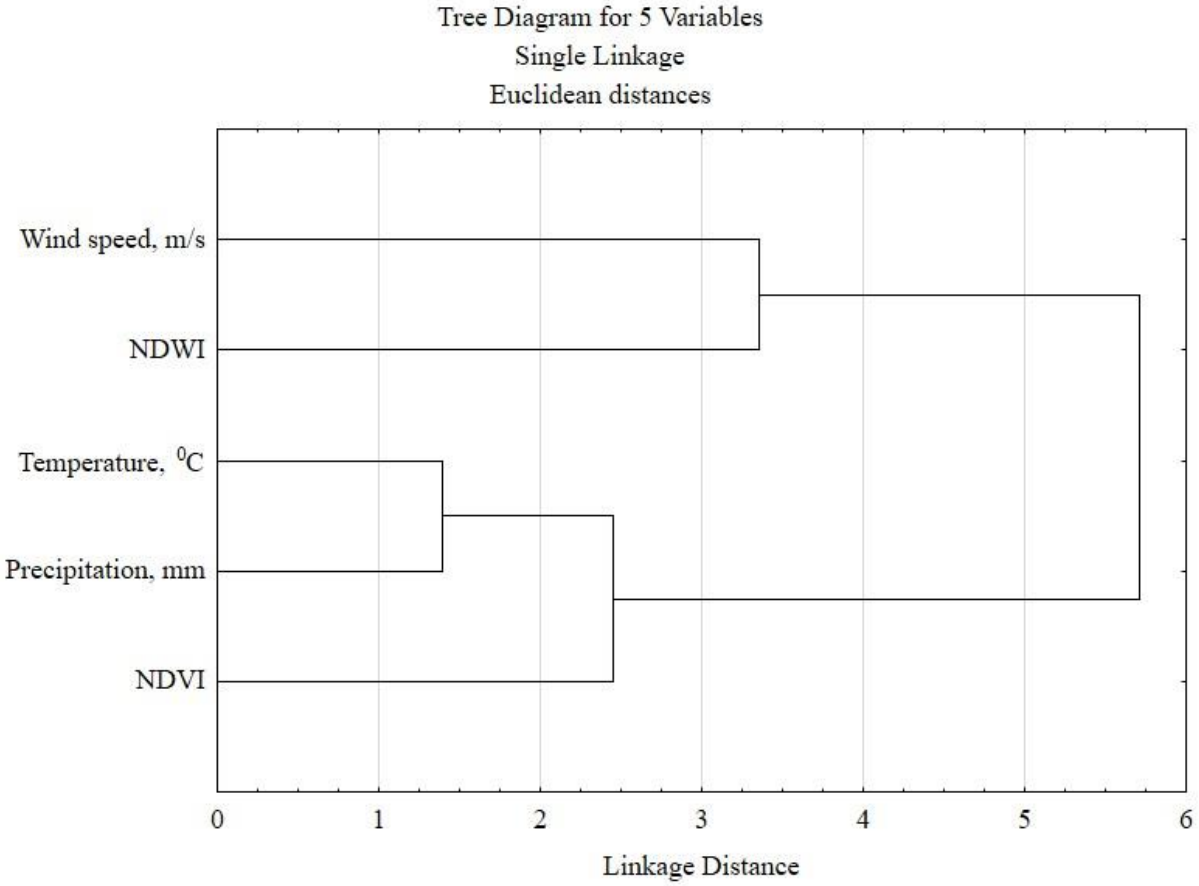


Figure 10: Cluster analysis

The clustering by month clearly forms only two groups: June-July and December-January-February-March. The first group defines the most favourable period for vegetation development due to moderate temperatures and frequent precipitation for the warm period. The second can clearly characterise the presence of a significant number of coniferous forests. Both of these groups characterise these periods as the ones that are most affected by climate.

Conclusion

The Perehinsk territorial community is a typical example that characterises the mountainous and foothill vegetation structure, which is important for sustainable development of the territory. The vegetation index of a territory is dependent not only on forestry activities, but, as can be seen from the results of the study, is also dependent on the factor of global temperature changes in the water balance of the territory. The satellite image interpretation data allowed us to summarise the dynamics of the vegetation index change for two similar periods, in particular, for 2018 it is 0.464, for 2023 is 0.330. The interpretation of the results of this study can serve only as one of the initial stages for studying the index, taking into account all possible factors that may occur. Interpretations are illustrated as below:

1. The extreme weather conditions observed in recent decades reduce the possibility of intensive vegetation development and form a downward trend in the NDVI index;
2. Thanks to the satellite imagery data, it is possible to analyse the state of vegetation cover and identify the main zones with the most affected areas;
3. Statistical analysis of the factors that determine meteorological and climatic indicators allowed us to outline the main relationships with the NDVI index through the correlation coefficient;
4. A comprehensive programme for sustainable development of territories should be developed to prevent negative consequences of anthropogenic activities due to unauthorised or excessive ‘sanitary’ deforestation; and
5. Further research on the impact of climate change on the state of vegetation cover will allow us to assess changes in the state of the environment in future periods, and to outline, together with specialists, the possibilities of forest cover for restoration through logging.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*
Conceived and designed the research or analysis	Yes	Yes
Collected the data	Yes	Yes
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	No	Yes
Editing of the article/paper	No	Yes
Supervision	No	Yes
Project Administration	No	Yes
Funding Acquisition	No	No
Overall Contribution Proportion (%)	30	70

Funding
No financial support was received for the research and writing of this article.

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(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)
The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

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